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Supercapacitors Energy Storage Based DSTATCOM Modeling and Simulation for Distribution System (Smart Grid)

[1]M.Abbas Khan, [2]Haider Ali, [3]Nouman Shah, [4]Dr.M Tariq
[1]Balochistan University of Information Technology Engineering and Management Sciences
[2,3]COMSATS IIT Abbottabad Campus KPK Pakistan
Corresponding Author Emails: [1]engineerabbaskhan111@gmail.com,[2]haiderali@ciit.net.pk

Abstract:DSTATCOM is a custom power device that is used to regulate the voltage sags/swells in the distribution system for maintaining the rated voltage level at the terminal of load/sensitive loads. The DSTATCOM can inject three-phase voltages at point of common coupling whose magnitude and phase angle can be regulated with PI controller, while the super capacitors are used to meet the instantaneous power demand since they can store and quickly release significant amounts of energy. This paper explores the use of Super capacitors in DSTATCOM in place of battery for control of load terminal voltage.

Keywords:DSTATCOM, Super capacitor, FLL,Regulation,

1. INTRODUCTION:

In recent years, Power engineers are increasingly concerned over the quality of the electrical power. Presently in modern industries, load equipment uses electronic controllers which are sensitive to poor voltage quality and will shut down if the supply voltage is and may mal-operate in other ways if harmonic Distortion of the supply voltage is excessive [1].DSTATCOM are used for improvement of power quality in the distribution system. But due to limited capability of delivering Quick/instantaneous real power they have limited ability to improve system performance.

Conventionally in the DSTATCOM battery is used for energy storage purpose, though batteries have a high energy density but do not possess instantaneous charge and discharge capabilities and normalized voltage swing (U_{min} /U_{max}) at open circuit for batteries is higher than 0.85.Therefore it cannot handle transient state problems efficiently. From the last decade, there have been considerable developments and improvements in energy storage technologies for example, SMES, Flywheel, Fuel Cells and also in the battery technologies .On the contrary, these technologies have some limitations, SMES require a lot of space, high shielding for its magnetic effect and complex auxiliary system, fuel cells quite slow initial response and batteries life expires very fast in case of full discharge and limited number of charge/discharge cycle[2,3,4].

The recent development of Super capacitors has given a hope in the field of energy storage technologies, which can store a very large amount of energy and it have very fast instantaneous power/energy charge and discharge capabilities in the regulated manner[5.6]. Using custom power devices, independent of number of charge and discharge cycle, voltage swing is 0.5 and is limited by the power conditioning system which do not allow the supercapacitors depth of discharge to go above 75% ,very high efficiency, life about 20-25 years and charge and discharge times are fractions of a second to several minutes. The energy stored in the SCESS is used to provide real power and reactive power through the inverter to the distribution network [7,8]. The aim of this research is to investigate the use of the super capacitors energy storage based DSTATCOM to enhance power quality of distribution system by means of fast & precise regulation of voltage sags/swells and control of
SCESS voltage level.

2. DESIGN OF SUPERCAPACITORS ENERGY STORAGE SYSTEM:

The purpose of connecting the SCESS inDSTATCOM for smoothing the power fluctuationvia charging and discharging the real power whichmay be due to peak demand, transient fault and otherreasons. Another application is voltage management across the load terminal. The super capacitorsvoltageUsc will drop to 0 V if all the stored energy is utilizedthen the constraint rated power output capabilitywould be violated i.e. $P_{stored} \geq P_{rated}$. Therefore a lowerlimit is fixed on the supercapacitors voltage Umin, is50 % of Umax, so that 75 % of stored energy can be utilizedefficiently. Since the voltage ofsupercapacitors cell is low therefore the supercapacitors bank would consist of number ofsupercapacitors cells in series andparallel so that therequired voltage level and sufficient useful energycan be stored. The schematic diagram is shown in the figure 01.

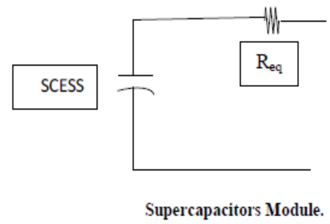

Figure 01: Super Capacitors Bank

In general, the number of series connected cells Ns in one branch are imposed by the rating ofSupercapacitors cells maximum voltage available in the market or in the stack.

$$N_s = \frac{U_{max}}{U_{cell}}$$

Where:
Ns = number of cell connected in series.
U_{max}= maximum voltage of the super capacitors bank.
U_{cell} = rating of super capacitors cell.

The number of parallel branch Np in the Super capacitors bank can be found by:

$$N_p = \frac{(N_s \times C_{eq})}{C_{cell}}$$

Where:
C_{eq}= equivalent capacitance of supercapacitors bank in Farad.
C_{cell}= capacitance of each cell in Farad.
Ns = number of cell connected in series.
Np= number of parallel arms in supercapacitorsbank.
The equivalent capacitance of the supercapacitorsbank is represented by the following formula:

$$C_{eq} = \frac{(N_p \times C_{cell})}{N_s}$$

Where:
Ceq = is equivalent capacitance of super capacitor bank in Farad
Ccell = is cell capacitance of each cell in Farad
Ns = are number of cell connected in series
Np = is number of parallel arms in super capacitor bank.
From the above equation, it is clear that to have net higher equivalent capacitance of the bank; number of the parallel arms Np should be always higher than Ns thereby higher energy storage capacity.
Total numbers of cell in Supercapacitors bank would be:

$$N_T = N_s \times N_p$$

Where:
NT = is total number of cell required in super capacitor bank
Ns = are number of cell connected in series
Np = is number of parallel arms in super capacitor bank.

The maximum energy store in the super capacitor bank:

$$E_{max} = \frac{(C_{eq} \times U_{max}^2)}{2}$$

Where:
Emax = is the maximum energy storage capacity
Ceq = is equivalent capacitance of super capacitor bank in Farad
Umax = is the maximum voltage of the super capacitor

The discharge voltage ratio the super capacitor bank is representation as following:

$$\%d = \frac{U_{min}}{U_{max}} \times 100$$

Where;
%d = is percentage discharge ratio
Umin = is the minimum allowable voltage limit of the super capacitor

The maximum power that can be withdrawn from the super capacitor bank can be expressed as following as per maximum power transfer theorem:

$$P_{Dmax} = \frac{U_{max}^2}{4R_{eq}}$$

Where:
PD_{max} = is the maximum dischargeable power in KW
R_{eq} = is equivalent series resistance of super capacitor bank in ohm

Once the voltage constraints have been obtained i.e. Umin< U <Umax then the useful energy (Eu) thatthe super capacitor bank can provide can be expressed as following:

$$E_u = C_{eq}\left[\frac{(U_{max} - U_{min})^2}{2}\right]$$

The proposed supercapacitors energy storage system is designed to have storage of 1 MWh (3600 MJ) of energy, voltage of 440Vand 1000 kW of peak powerconnected to distribution system to supply the load in case of voltage variation and additional power demand. The supercapacitors used are of having product

Minimum Voltage is defined as 50% of V_{max}i.e. V_{surge}, so that 75% of stored energy can be utilized.
V_{min} = 17*50% = 8.5V
The total capacitance of supercapacitor bank in Farads is given as follows:
C_{eq} = C_{cell} * (# of parallel / # of series)
C_{eq} = 500 * (1/6) = 83.33 F

The maximum energy storage capacity in the bank is:

E_{max} = (C_{eq} * V_{max}^2) / 2
E_{max} = (83.33*289)/2 = 12.04 KJ
The percentage discharge voltage ratio in the bank is represented as:
%d = (V_{min}/V_{max})*100
%d = (8.5/17)*100
%d =50%

The maximum dischargeable power that can be withdrawn from the supercapacitor bank is expressed as following using the maximum power transfer theorem:

P_{Dmax} = V_{max}^2/4R_{eq}
P_{Dmax} = 17^2/ (4*2.1e^{-3}) =289/0.418
P_{Dmax}=691.03 W

As the voltage constraints have been obtained i.e.
V_{min}<V_w<Vmax
8.5 < 16 < 17

So, the useful energy (E_u) that the supercapacitor bank can provide is given as:
E_u = C_{eq}*[(V_{max}-V_{min})^2/ 2]
E_u = 83.33*[72.25/2]= 83.33*36.12
E_u= 3.01 KJ

3. SIMULINK MODELING OF THE DSTATCOM AND ITS CONTROL:

A DSTATCOM which consists of a two level voltage source converter as inverter, supercapacitorsbank as energy storage device, a couplingtransformer connected in shunt to the distributionnetwork .The voltage source converter converts thedc voltage of the super capacitors bank into sets of three phase ac

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voltages as output .These voltages arein phase and coupled with the distribution systemthrough reactance of the coupling transformer. Theproper adjustment of the phase and magnitude of theDSTATCOM output voltages allows effectivecontrol of the active and reactive power exchanges between the DSTATCOM and the distribution network.

The VSC connected in shunt with the distribution network can be used for voltage regulation and compensation of reactive power, power factor correction and elimination of harmonics. The continuous voltage regulation of the distribution network is performed by injecting the shunt current for elimination of the voltage sag across the system impedance. The value of current can be controlled by adjusting the output voltage of the converter. The efficacy of the DSTATCOM in correcting voltage sag depends on the value of equivalent Theveninimpedance of the system or the fault level of the load bus. When the shunt injected current is in quadrature with the load terminal voltage, the desired voltage correction can be achieved without injection of the active power into the distribution network. On the other hand, when the value of shunt current is minimized, the same voltage correction can be achieved with minimum apparent power injection into the system.

The control scheme for the DSTATCOM is shown in the Figure below .The controller input is an error signal obtained from the DC reference voltage and the measured terminal voltage of the SCESS .Such error is processed by a discrete PI controller and the output is Id_ref, which is provided to current regulator. The current regulator output is passed to sinusoidalvoltage error generator; this error signal is provided to discrete PWM signal generator. The PWM generator generates the pulse signals that are passed to voltage source converter togenerate the output voltage as per load requirement on the point of common coupling.

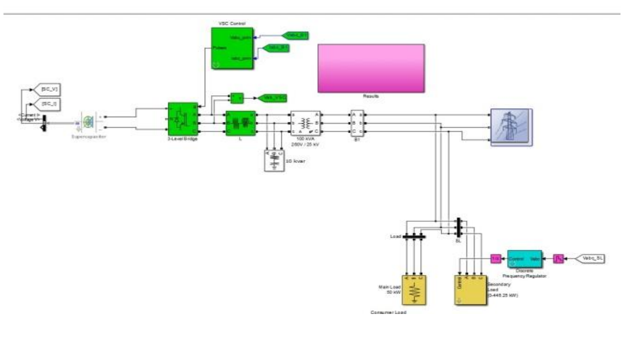

Fig.02: Energy Storage System Model

Figure 02 shows the MATLAB/ SIMULINK simulation model that was built for Supercapacitor energy storage system feeding power to the stand alone electrical power generating plant. The test system comprises of 120 KV, 60 Hz transmission system of 30 km long and T-section of 2km long feeding into the primary side of the 2- winding transformer connected in the Y/Δ, 120kV /260V, 100KVA, speed and torque of the engine until the undesirable stop. The load is connected to 260V secondary side of the transformer.

The DC voltage is applied to IGBT/Diodes of the two levelinverter generating 50 Hz. The IGBT of the inverter uses pulse width modulation at 1680 Hz carrier frequency, and discretized sample time of $5.8e^{-6}$sec.The load voltage is regulated at 1 PU by PI voltage regulators of dc regulator, the input of DC regulator are voltage of PCC, current of PCC, SCESS voltage and the output is a vector containing the three modulating signals used by the discrete pulse width modulation generator to generate the 6 IGBT pulses. The harmonics generated by the inverter are filtered by LC filter. The three coupling transformer of 260V/120 kV, 100KVA are used to connect the DSTATCOM to the distribution network. A SCESS of 13912.9 F are connected on the dc side to provide the energy/real power. A PLL (phase locked loop) block is also used in the above model for frequency control. The internal diagram of the PLL is shown below:

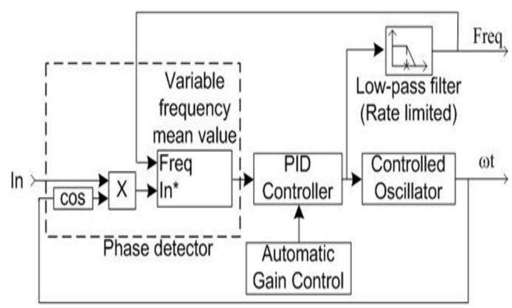

Figure03: Phase Loop Lock Diagram

4. SIMULATION RESULTS:

CASE (1) - *SIMULATION RESULTS WHEN SUPER CAPACITORS ARE CHARGED 40% BELOW THE STATE OF CHARGE OR BELOW THE Umin:*

Simulations was carried out but the DSTATCOM super capacitors had been discharged below the Uminlevel, while the three phase circuit breaker for duration 0.2 - 0.3 sec in which main line supply was cutoff, but now the voltage across the load in phases is able to maintain but for the third phase the DSTATCOM was not able to supply the power properly as required. The voltage and current waveforms are shown respectively in figures below:

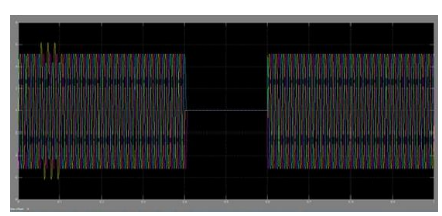

Fig.4.2 (a) Current through the load when supercapacitors are charged below Umin

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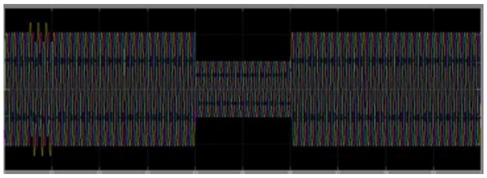


Fig.4.2 (b) Current through the transformer when supercapacitors are charged below Umin

CASE (2) - *SIMULATION RESULTS WHEN SUPER CAPACITORS ARE FULLY CHARGED:*

The SCESS are fully charged and the main supply to load is switched off by the three phase circuit breaker for period of 0.2-0.3 second. During this period thesupercapacitor energy storage arrangement is able to supply energy to the distribution network and all the system parameter maintains its desired value as shown in the Figures below 4.3 a, b.

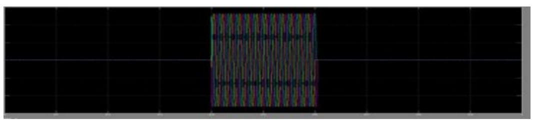
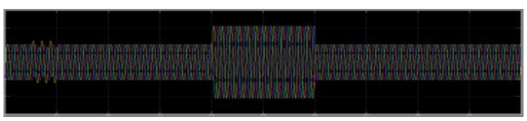


Fig.4.3 (a) Current through the load when supercapacitors are fully charged



.4.3 (b) Current through the transformer when supercapacitors are fully charged

5. RESULT ANALYSIS:

We applied 30% extra load to the Electrical Generator Set for a period of 0.2 – 0.3 second. It creates 87.5% ofvoltage drop and 5.33% frequency variation at thegenerator terminals. During this period current decreases up to 50% of its rated value as shown in the Case (1). Afterwards we decrease the load and extra power is delivered to supercapacitor to charge it. When the supercapacitors are fully charged and able toprovide power to the load the value of voltage reaches itsrated value i.e. 400V and frequency variations came underits permissible limits as shown in Case (2).

6. CONCLUSION:

The supercapacitor based energy storage system designedfor energy stabilization and maintaining the voltageprofile as well as frequency regulation of the standalonepower plant which supplies power to the distributionnetwork via inverter is 260V.Supercapacitors energy storage system has been used as astorage device and deliver the real power into distributionnetwork for higher rate of change of dynamic conditionsin case of transient conditions as well as for averagepower demand in case of steady conditions. The highlydeveloped graphic facilities available in MATLAB/SIMPowerSimulink were used to conduct all aspects of modelimplementation and to carry out extensive simulationstudies in the developed test systems. A PWM basedcontrol scheme has been implemented to control theswitches (IGBT/Diode) in the two level voltage sourceconverters which control the supercapacitorstodeliver/absorb the real power as per the requirement. Asthe simulation result shows that SCESS arrangementimproves the performance of distribution network alsofound able to mitigate the voltage sags as well as frequency regulation. Its characteristics make it more suitable with non-conventional energy sources for energy stabilizing purpose.

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